

CLAIMS

What is claimed is:

- 1 1. A quantum dot vertical cavity surface emitting semiconductor laser
- 2 (VCSEL), comprising:
- 3 a first distributed bragg reflector (DBR) mirror disposed on a substrate
- 4 layer comprised of a first plurality of mirror pairs with each mirror pair
- 5 including layers having a step change in indices of refraction;
- 6 a second distributed bragg reflector (DBR) mirror comprised of a
- 7 second plurality of mirror pairs with each mirror pair including layers having a
- 8 step change in indices of refraction;
- 9 a semiconductor quantum dot active region disposed between a top of
- 10 the first DBR mirror and a bottom of the second DBR mirror, the quantum dot
- 11 active region including a plurality of quantum dots embedded in a plurality of
- 12 quantum wells disposed proximate at least one antinode of a longitudinal optical
- 13 mode, the quantum dots having a corresponding optical confinement factor;
- 14 first and second doped semiconductor intracavity contact layers each
- 15 having a thickness of no more than about half a wavelength disposed between
- 16 the first and second DBR mirrors positioned and doped to inject electron-hole
- 17 pairs into the quantum dot active region in response to a drive current;

18 the mirror pairs of at least one of the DBR mirrors comprised of a
19 semiconductor layer and an oxidizable semiconductor layer which has been
20 oxidized to form a material with a refractive index substantially lower than the
21 unoxidized semiconductor, increasing the reflectivity of the mirror; and
22 at least one mode control layer disposed between the top of the first
23 DBR mirror and the bottom of the second DBR mirror forming a refractive index
24 profile to increase optical confinement of the quantum dot active region and
25 reduce optical confinement in the contact layers.

1 2. The VCSEL of claim 1, wherein the number of quantum dot layers,
2 the optical confinement of the quantum dot layers, and an optical overlap in
3 doped contact layers is selected to achieve a threshold gain that is less than a
4 saturated gain of a ground state of the quantum dots over a temperature range
5 between about 0 °C to about 85 °C.

1 3. The VCSEL of claim 2, wherein the active region has a longitudinal
2 thickness that is about an integer number of half wavelengths in the laser at a
3 target emission wavelength.

1 4. The VCSEL of claim 1, wherein each mode control layer has a
2 longitudinal thickness of about one quarter of the emission wavelength in the
3 laser, has a refractive index different than adjacent layers, and is positioned in the
4 cavity to form a resonant reflection acting to increase the longitudinal mode

5 intensity in the quantum dot active region and decrease the longitudinal mode
6 intensity in the contact layers.

1 5. The VCSEL of claim 4, wherein there is a first mode control layer
2 disposed between a first end of the active region and the first mirror and a
3 second mode control layer disposed between a second end of the active region
4 and the second mirror.

1 6. The VCSEL of claim 5, wherein each mode control layer is disposed
2 between an end of the active region and a heavily doped contact layer.

1 7. The VCSEL of claim 1, wherein the second DBR mirror comprises
2 mirror pairs having an oxide layer and a semiconductor layer.

1 8. The VCSEL of claim 7, wherein the first DBR mirror comprises
2 mirror pairs having a semiconductor layer and an oxidizable semiconductor
3 layer with at least one opening is formed in the first DBR mirror through the
4 oxidizable semiconductor layer to laterally oxidize the oxidizable layers with a
5 laterally connecting portion of the first DBR mirror along at least one side of the
6 first DBR mirror to inhibit delamination of the first DBR mirror.

1 9. The VCSEL of claim 1, wherein the at least one DBR mirror
2 comprised of a semiconductor layer and an oxidizable semiconductor layer
3 further comprises: an intermediate layer disposed between the semiconductor

4 layer and the unoxidizable semiconductor layer having a composition selected to
5 inhibit delamination of the oxidized DBR mirror.

1 10. The VCSEL of claim 8, wherein the substrate is a GaAs substrate
2 and the quantum dots comprise self-assembled InAs quantum dots formed in
3 InGaAs quantum wells, and the DBR mirrors layers comprise alternating layers
4 of $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{Al}_y\text{Ga}_{1-y}\text{As}$, where x is greater than y .

1 11. The VCSEL of claim 10, wherein the Al molar fraction of the
2 $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer is selected to be between about 0.95 to 0.99 whereby the
3 oxidation rate of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer is controlled.

1 12. The VCSEL of claim 1, wherein there is a first mode control layer is
2 disposed between a first end of the active region and the first mirror and a
3 second mode control layer disposed between a second end of the active region
4 and the second mirror, each mode control layer having a longitudinal thickness
5 of about one quarter of the emission wavelength in the laser, has a refractive
6 index different than adjacent layers, and is positioned to form a resonant
7 reflection acting to increase the longitudinal mode intensity in the quantum dot
8 active region and decrease the longitudinal mode intensity in the contact layers.

1 13. The VCSEL of claim 12, wherein each mode control layer has a
2 refractive index lower than adjacent layers.

1 14. The VCSEL of claim 13, wherein the active region has a thickness that is
2 approximately an integral number of half wavelengths in the laser.

1 15. The VCSEL of claim 12, wherein each mode control layer has a refractive
2 index higher than adjacent layers.

1 16. The VCSEL of claim 15, wherein the active region has a thickness that is
2 approximately an odd number of quarter wavelengths.

1 17. A vertical cavity surface emitting semiconductor laser (VCSEL),
2 comprising:

3 a first distributed bragg reflector (DBR) mirror;

4 a second distributed bragg reflector (DBR) mirror spaced apart from
5 the first mirror to form a microcavity for a longitudinal optical mode;

6 a semiconductor quantum dot active region having a first end and a
7 second end disposed in the microcavity between the mirrors;

8 first and second doped semiconductor intracavity contact layers
9 disposed in the microcavity on opposed ends of the quantum dot active region
10 doped to inject electron-hole pairs into the quantum dot active region in response
11 to a drive current;

12 at least one mode control layer disposed in the microcavity;

13 the at least one mode control layer having a refractive index profile for
14 generating reflections within the microcavity which create a resonance condition

15 that increases optical confinement in the active region and decreases optical loss
16 in contact layers.

1 18. The laser of claim 17, wherein each mode control layer is approximately
2 a quarter of a wavelength in thickness and has a refractive index profile different
3 than adjacent layers.

1 19. The laser of claim 18, wherein each mode control layer is disposed
2 between the active region and a heavily doped portion of a contact layer.

1 20. The laser of claim 17, wherein at least one of the DBR mirrors is an
2 ultrahigh reflectivity DBR mirror formed by laterally oxidizing DBR mirror pair
3 layers that include an oxidizable semiconductor layer and a substantially non-
4 oxidizable semiconductor layer.

1 21. The laser of claim 20, further comprising an intermediate composition
2 layer disposed between the oxidizable semiconductor layer and the substantially
3 non-oxidizable semiconductor layer to inhibit delamination.

1 22. The laser of claim 20, wherein the first mirror is formed into a mesa
2 laterally oxidized along at least one side; and

3 the second mirror has its bottom surface disposed on a substrate layer,
4 the second mirror having at least one cavity disposed through it through which
5 the second mirror is oxidized and at least one connecting section providing
6 lateral support.

1 23. The laser of claim 21 wherein the laser has a threshold gain less than a
2 saturated gain of a ground state of the quantum dots in a temperature range
3 between about 0 °C and 85 °C.

1 24. A vertical cavity surface emitting laser, comprising:

2 first and second distributed bragg reflector (DBR) mirror means for
3 forming an optical cavity between the mirror means having optical feedback;

4 quantum dot active means disposed within the optical cavity for
5 providing optical gain responsive to a current;

6 intracavity contact layer means for providing current to the quantum dot
7 active means; and

8 resonant mode control layer means disposed between the mirror
9 means for increasing the optical confinement of the quantum dot active means
10 and reducing the optical intensity in the contact layer means.

1 25. The laser of claim 24, further comprising:

2 delamination inhibition means for inhibiting the delamination of the
3 high reflectivity mirror means.

1 26. The laser of claim 24, wherein a threshold gain of the laser is less than a
2 saturated ground state gain over a temperature range between about 0°C to
3 85°C.

1 27. A method of forming a vertical cavity surface emitting laser having an
2 oxidized bottom distributed bragg reflector (DBR) mirror with lateral support,
3 comprising:

4 etching at least one opening into mirror layers of the bottom DBR mirror,
5 the at least one cavity disposed proximate an outer perimeter of a lasing portion
6 of the bottom DBR mirror with at least one lateral connecting portion of the
7 mirror layers remaining to support the lasing portion of the mirrors; and
8 laterally oxidizing the mirror layers of the bottom DBR mirror.

1 28. The method of claim 27, wherein the bottom DBR mirror includes
2 AlGaAs layers and the mirror layers are oxidized in steam.

1 29. The method of claim 28, wherein the mirror layers comprise AlAs/GaAs
2 layers laterally oxidized to AlO/GaAs.

1 30. The method of claim 29, further comprising an intermediate
2 composition layer disposed between the AlAs and GaAs layer.

1 31. The method of claim 30, wherein the AlAs layer comprises a molar
2 fraction of gallium of at least about 0.01 for improved control of lateral oxidation
3 rates.

1 32. A vertical cavity surface emitting laser fabricated by the method of
2 claim 27.

1 33. A method of forming a vertical cavity surface emitting laser with
2 intracavity contacts from a substrate having a top DBR mirror with DBR mirror
3 layers, a bottom DBR mirror with DBR mirror layers, a top contact layer, an
4 active region, and a bottom contact disposed between the mirrors, the method
5 comprising:
6 etching a top mirror mesa to expose the top contact layer outside of a top
7 mirror for the VCSEL;
8 masking the top mirror mesa and etching down to the bottom contact layer;
9 etching at least one opening into mirror layers of the bottom DBR mirror,
10 the at least one opening disposed proximate an outer perimeter of a lasing
11 portion of the bottom DBR mirror with at least one lateral connecting portion of
12 the layers remaining to support the lasting portion of the mirrors; and
13 laterally oxidizing the mirror layers of the bottom DBR mirror through the
14 at least one opening.

1 34. The method of claim 33, further comprising: depositing a top contact
2 metallization on a portion of the top contact forming a metal contact on the top
3 contact layer about the top mirror mesa leading to a contact pad prior to etching
4 down to the top contact layer.

1 35. The method of claim 33, further comprising: depositing a bottom
2 contact metallization on a portion of the exposed bottom contact layer prior to
3 etching through the bottom mirror layers.

1 36. The method of claim 33, wherein the bottom DBR mirror layers include
2 AlGaAs layers with an aluminum molar fraction greater than 0.90 and the
3 AlGaAs layers are laterally oxidized in steam.

1 37. The method of claim 36, wherein the bottom DBR mirror layers are
2 oxidized at a temperature of less than 450 °C.

1 38. A vertical cavity surface emitting lasers fabricated by the process of
2 claim 33.

1 39. A vertical cavity surface emitting lasers fabricated by the process of
2 claim 36.

1